

Ding, Y., Meriggi, L., Steer, M. J., Bulashevich, K., Thayne, I. G., MacGregor, C., Sorel, M., and Ironside, C. (2014) *An investigation of MWIR AlInSb LEDs based on double heterostructures and multiple quantum wells*. In: 2014 Conference on Optoelectronic and Microelectronic Materials and Devices (COMMAD2014), 14-17 Dec 2014, Perth, Australia.

Copyright © 2014 The Authors

A copy can be downloaded for personal non-commercial research or study, without prior permission or charge

Content must not be changed in any way or reproduced in any format or medium without the formal permission of the copyright holder(s)

<http://eprints.gla.ac.uk/97806/>

Deposited on: 02 October 2014

An investigation of MWIR, AlInSb LEDs based on double heterostructures and multiple quantum wells

Ying Ding, *Member, IEEE*, Laura Meriggi, *Graduate Member, IEEE*, Matthew J. Steer, Kirill Bulashevich, Iain G. Thayne, Calum MacGregor, Marc Sorel, and Charles N. Ironside, *Senior Member, IEEE*

Abstract—Mid-infrared LEDs based on AlInSb double heterostructure and multiple quantum well active regions have been simulated and investigated using the SimuLED software package from STR. The simulation results indicate that the double heterostructure and multiple quantum well active regions offer higher carrier injection efficiency and energy conversion. This translates into an output power and wall-plug efficiency that are three and two times higher, respectively, than a conventional homojunction active region.

Index Terms—Mid-infrared, Light emitting diodes (LEDs), Electroluminescence (EL), Quantum wells

I. INTRODUCTION

Semiconductor materials such as antimonide emitting in the 3–5 μm mid-infrared band are of great interest for the development of a low-cost photonic technology for the next generation of miniature and energy-efficient CO, CO₂, CH₄ gas sensors [1]. A well-established and cost effective approach is to directly grow the antimonide-based epilayer on a GaAs substrate. A buffer layer several μm thick is grown on top of the wafer to accommodate the large lattice mismatch [2]. Standard epilayer designs for LEDs employ a homojunction active region in combination with a relatively wide bandgap barrier between the active region and p-doping layer to reduce carrier leakage [1, 3, 4]. However, the carrier leakage in a homojunction design is still a major problem because of the efficiency droop under a high current density [5]. Here, we report on an investigation of multiple quantum well (MQW) heterostructures as a means of increasing the efficiency of the mid-IR LEDs.

The carrier injection efficiency and carrier concentration distributions on the epitaxial structures with double heterostructure (DH) and MQW active regions were

Ying Ding, Laura Meriggi, Matthew J. Steer, Iain G. Thayne, and Marc Sorel are with Electronic and Nanoscale Engineering, School of Engineering, University of Glasgow, G12 8LT, Glasgow UK (corresponding author to provide phone: 0044-141-330-6022; e-mail: ying.ding@glasgow.ac.uk).

Kirill Bulashevich is with STR Group, Inc. – Soft-Impact, Ltd. Engels av. 27, P.O. Box 89, 194156, St. Petersburg, Russia.

Charles N. Ironside was with Electronic and Nanoscale Engineering, School of Engineering, University of Glasgow, G12 8LT, Glasgow UK. He is now with Department of Imaging and Applied Physics, Curtin University, Perth 6845 Western Australia.

Matthew J. Steer and Calum MacGregor are with Quantum Device Solutions, The West of Scotland Science Park, Block 7 Kelvin Campus, G20 0TH, Glasgow UK.

TABLE I

Sequence of layers for the mid-infrared AlInSb bulk epi-grown structure from top to substrate (homojunction)

Layer thickness (nm)	Material	x	Type	Conc. (cm ⁻³)
500	Al(x)In(1-x)Sb	0.05	p	7E+17
20	Al(x)In(1-x)Sb	0.2	p	7E+17
1000	Al(x)In(1-x)Sb	0.05	i(n)	9E15
3000	Al(x)In(1-x)Sb	0.05	n	7E17
300	GaSb			
GaAs Substrate				

TABLE II

Sequence of layers for the mid-infrared AlInSb bulk epi-grown structure from top to substrate (DH)

Layer thickness (nm)	Material	x	Type	Conc. (cm ⁻³)
500	Al(x)In(1-x)Sb	0.09	p	7E+17
20	Al(x)In(1-x)Sb	0.2	p	7E+17
1000	Al(x)In(1-x)Sb	0.05	i(n)	9E15
3000	Al(x)In(1-x)Sb	0.09	n	7E17
300	GaSb			
GaAs Substrate				

investigated using the SimuLED software package from STR. In particular, the relationship of the injection efficiency, on the number of quantum wells, and bias voltage was analyzed in detail. LED devices based on an optimized seven well MQW structure were fabricated and measured. The results confirm the theoretical predictions and indicate that MQW LEDs can have an output power 2 to 3 times higher than LEDs with a homojunction active region.

II. EPI STRUCTURES AND SIMULATIONS

The conventional homojunction bulk structure is shown in Table 1. The epi-layers consist of a GaSb buffer layer, a 3- μm n-type doping layer, followed by a 1- μm undoped active layer and a 0.5- μm p-type layer. A 20-nm p-type Al_{0.2}In_{0.8}Sb barrier layer was grown between the p-layer and active layer in order to reduce carrier leakage [3, 4]. The investigated DH bulk structure is shown in Table 2. Only the Al content in the p-type and n-type layers was increased from 0.05 to 0.09 to form the heterojunction barriers. For the MQW structures, we used doped Al_{0.2}In_{0.8}Sb as the confinement layers and the designed MQW consisted of three to twenty 15-nm Ga_xIn_{1-x}Sb quantum wells/20-nm Al_yGa_{1-y-z}Sb quantum barriers instead of bulk material as the active region. The center

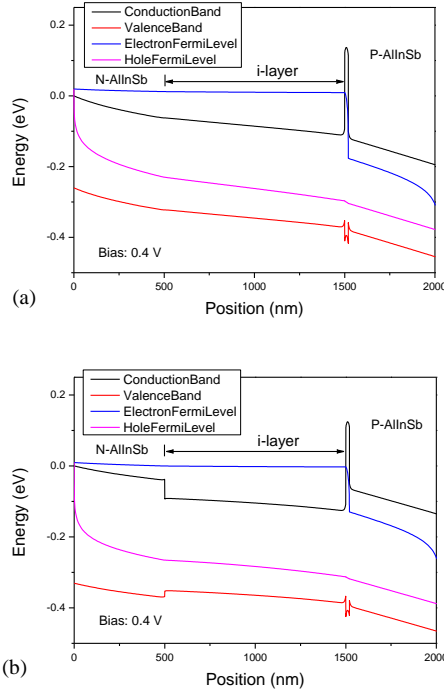


Fig. 1. Energy-band diagrams of mid-infrared AlInSb bulk structures: (a) homostructure; (b) DH.

emission wavelength for all structures was designed at around $4.3 \mu\text{m}$ for the absorption and detection of carbon dioxide.

The band diagrams of the conventional homostructure and the DH bulk structures under the bias voltage of 0.4 V are shown in Fig. 1 (a) and (b), respectively. As expected, for larger barriers, a corresponding improvement in the carrier confinement can be seen from the DH band diagram. Fig. 2 shows the carrier concentration distribution for the homostructure and the DH bulk structures under a bias voltage of 0.4 V . The carrier concentrations in DH are higher than that in homostructure active region, which indicates a reduced carrier leakage, especially at the n-type AlInSb side. A further advantage is that a more uniform carrier concentration distribution can be obtained in the DH active region. Fig. 3(a) compares the simulated injection efficiency as a function of the bias voltage for the mid-infrared AlInSb bulk structures with homostructure and DH active regions. The injection efficiency of the DH active region is much higher than that of the homostructure active region. The I-V characteristics of Fig. 3(b) indicate that the inclusion of a DH active region does not change the diode electrical performance.

Figure 4 shows the simulated injection efficiency as a function of bias voltage and the I-V characteristics of mid-infrared AlInSb devices with MQW structures. The quantum well numbers are 3, 5, 7, 10, 15, and 20. As expected, the injection efficiency increases with increasing quantum well number and the injection efficiency decreases with increasing bias voltage. It is possible to further enhance the carrier confinement by increasing the energy band offset of the barriers, thereby further improving the injection efficiency.

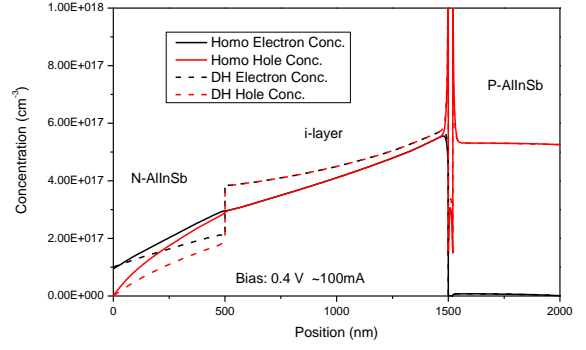
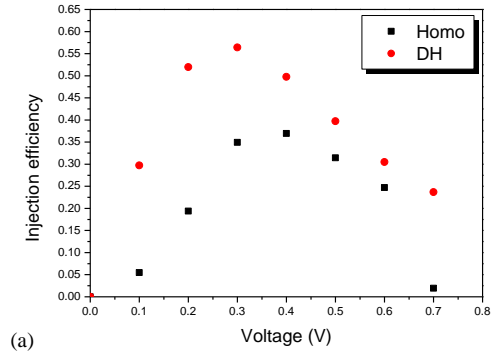
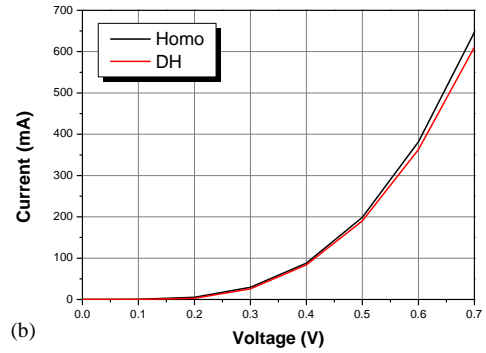


Fig. 2. Carrier concentration distribution of mid-infrared AlInSb bulk structures: homostructure vs. DH.



(a)



(b)

Fig. 3. (a) Simulated injection efficiency as a function of bias voltage, (b) I-V curves of mid-infrared AlInSb bulk structures: homostructure vs. DH.

III. EXPERIMENTAL RESULTS OF MQW LEDs

An AlInSb epitaxial wafer with a seven wells MQW structure was grown and the AlInSb LEDs were fabricated following the fabrication procedure described in [1]. Fig. 5 (a) compares the EL spectra of the mid-infrared AlInSb LEDs with MQW and with homostructure active regions obtained with pulsed current of 100 mA (1-kHz frequency and 10% duty cycle). A three-times improvement in the peak intensity can be observed from the MQW active region under the same operating current conditions. The spectra of Fig. 5 (b) show

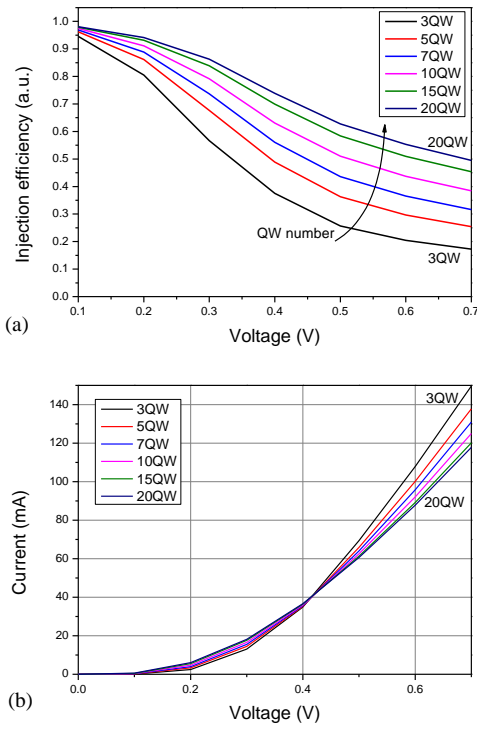


Fig. 4. (a) Simulated injection efficiency as a function of bias voltage, (b) I-V curves of mid-infrared AlInSb with MQW structures.

that a similar peak intensity is emitted when an electrical power of ~ 1 mW and ~ 2 -mW are injected in the MQW LED and the homojunction LED, respectively. The reason for which the improvement in wall-plug efficiency is not as pronounced as that measured for the EL intensity is due to the higher contact resistivity of the MQW epilayer.

IV. CONCLUSION

Mid-infrared AlInSb LEDs based on DH and MQW active regions have been investigated. Simulation results show that a better carrier confinement and a more uniform carrier distribution in active region can be attained by including DH and MQW active regions in the epilayer design. The experimental results indicate that a DH-MQW design can provide a three-times increase in output power and a two-times increase in the wall-plug efficiency compared to a homojunction design.

ACKNOWLEDGMENT

Y.D. would like to thank the technical staff of the James Watt Nanofabrication Centre at the University of Glasgow.

REFERENCES

- [1] L. Meriggi, M.J. Steer, M. Sorel, C.N. Ironside, I.G. Thayne, and C. MacGregor, "Mid-wave infrared (3-5 μm) AlInSb-based resonant-cavity LEDs," *CLEO/Europe*, 2013.
- [2] G.R. Nash, S.J. Smith, S.D. Coomber, S. Przeslak, A. Andreev, P. Carrington, M. Yin, A. Krier, L. Buckle, M.T. Emeny, and T. Ashley, "Midinfrared GaInSb/AlGaInSb quantum well laser diodes grown on GaAs," *Appl. Phys. Lett.*, 2007, 91, pp: 131118 1-3.

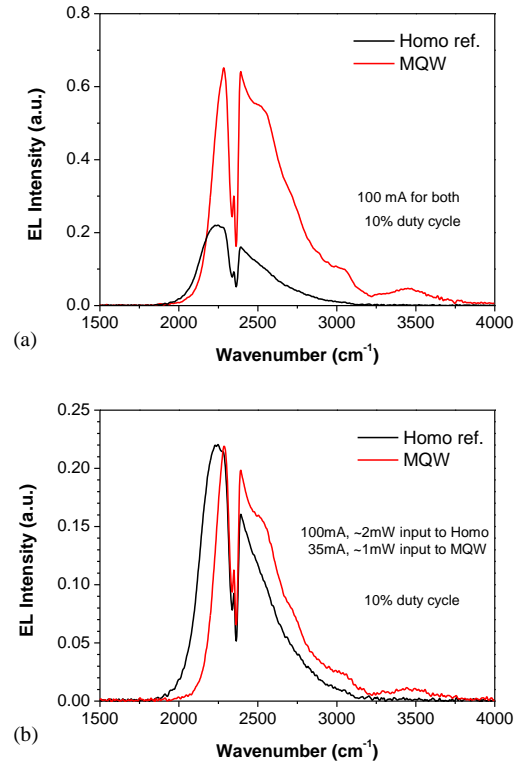


Fig. 5. Comparison of EL spectra of mid-infrared AlInSb LEDs with homojunction (as a reference) and MQW active regions, (a) under the same 100-mA pump current conditions; (b) with the same peak intensity. The dip in the spectra at around 2350 cm^{-1} is due to CO_2 absorption in the lab.

- [3] M. K. Haigh, G. R. Nash, S. J. Smith, L. Buckle, M. T. Emeny, and T. Ashley, "Mid-infrared $\text{Al}_x\text{In}_{1-x}\text{Sb}$ light-emitting diodes," *Appl. Phys. Lett.*, 2007, 90, pp: 231116 1-3.
- [4] E.G. Camargo, K. Ueno, Y. Kawakami, Y. Moriyasu, K. Nagase, M. Satou, H. Endo, K. Ishibashi, N. Kuze, "Miniaturized InSb photovoltaic infrared sensor operating at room temperature," *Opt. Eng.*, 2008, 47(1), pp: 014402 1-7.
- [5] L. Meriggi, M.J. Steer, Y. Ding, I.G. Thayne, C. MacGregor, C.N. Ironside, and M. Sorel, "Enhanced emission from mid-infrared AlInSb LEDs with p-type contact grid geometry," unpublished.